Insights into the history and timing of post-European land use disturbance on sedimentation rates in catchments draining to the Great Barrier Reef

Rebecca Bartley[a,*], Chris Thompson[b], Jacky Croke[c], Tim Pietsch[d], Brett Baker[e], Kate Hughes[b], Anne Kinsey-Henderson[e]

[a] CSIRO, Brisbane, Queensland 4068, Australia
[b] School of Geography, Planning and Environmental Management, University of Queensland, St Lucia, Brisbane 4072, Australia
[c] GeoSciences, Southern Cross University, Lismore, NSW, Australia
[d] Australian River Institute, Griffith University, Brisbane, Australia
[e] CSIRO, Townsville, Australia

A B S T R A C T

Sediment runoff has been cited as a major contributor to the declining health of the Great Barrier Reef (GBR), however, climate and land use drivers have not been jointly evaluated. This study used alluvial archives from fluvial benches in two tributaries of the Upper Burdekin catchment together with the best available land use history and climate proxy records to provide insights into the timing of depositional events in this region over the past 500 years. This study suggests that mining and the increased runoff variability in the latter half of the nineteenth century are the likely sources of the original excess sediment that was used to build the bench features in these catchments. Grazing also contributed to increased bench sedimentation prior to 1900, however, the contribution of grazing was likely more significant in the second half of the 20th century, and continues to be a dominant land use contributor today.

1. Introduction

Increased delivery of sediments and nutrients to the Great Barrier Reef (GBR) are considered to be one of the key contributors to the decline in the health of the reef ecosystem (De'ath et al., 2012). Geo-chronological data collected from marine cores have suggested that 'land-use practices such as clearing and overstocking have led to major degradation of the semi-arid river catchments, resulting in substantially increased sediment loads entering the inner Great Barrier Reef' (McCulloch et al., 2003). However, changes in climate and associated runoff have not been jointly evaluated alongside the impacts from land use. Recent data suggests that changes in land use were coincident with changes in climate (El Nino Southern Oscillation or ENSO) around ~1850 (Lough et al., 2015).

The timing and rate of sediment accumulation in alluvial storage features represents a useful means of assessing the degree to which catchment or environmental conditions have varied over timescales ranging from decades to thousands of years (Rustomji and Pietsch, 2007; Portenga et al., 2016). Sediment storage, and transfer from storage, may be used to explain the discrepancy between sediment erosion

and sediment yield (Trimble, 1981; Fryirs, 2013) and sediment storage and transfer may be the single most important aspect of determining how a river system responds to environmental change (Phillips, 1991).

Dating of alluvial sediments have been used to provide insights into the long term evolution of rivers and floodplains (Hughes et al., 2009; Wasson et al., 2010; Croke et al., 2011; Thompson et al., 2016), estimate sediment storage in within-channel bench deposits (Pietsch et al., 2015) and provide an understanding of the impact of catchment land use history on sedimentation rates (Hughes et al., 2009; Munoz-Salinas et al., 2014; McCloskey et al., 2016; Shellberg et al., 2016).

This study focuses on bench deposits which are defined as within-channel flat topped depositional features that are often vegetated, elongate, bank attached and discontinuous (Erskine and Livingstone, 1999). A review and detailed description of bench features is provided by Kermode et al. (2015). Bench formation has been attributed to a range of processes including changes in flow and flood magnitude due to changes in climate (e.g. drought) or anthropogenic activity (e.g. dams). Benches are also more likely to occur in regions subject to aridity that have high coarse sediment loads (Kermode et al., 2015). In Australia, bench accretion and formation has been shown to occur in

moderate flood events, with large flow events responsible for bench destruction and removal (Erskine and Warner, 1988).

Pietsch et al. (2015) put forward three possible explanations for the formation of bench features in tropical systems, including that benches: (1) have a lifespan of one to two centuries, before they are destabilised and removed; (2) are the result of channel expansion that has occurred following a change in flow regime; and (3) are the product of increased sediment production due to increased erosion following European settlement. In that study, the authors consider explanation (3) as the most plausible for bench development in the Normanby catchment, however, no detailed description of the type and magnitude of land use change was given. Several other studies have also determined benches to be, in part, post-settlement alluvial features (e.g. Rustomji and Pietsch, 2007; Hughes et al., 2009; Portenga et al., 2016). In contrast, Wasson et al. (2010) found bench deposits > 500 years old on the Daly River in the Northern Territory. They determined that the sediment source was the result of natural hydrologic change, with no discernible role for land use. Sand transport was most likely triggered from the sandy terrain in the upper Daly catchment by intense rainfall, and moved downstream by subsequent flows.

The aim of this study is to use the alluvial archives from benches in two tributaries of the Upper Burdekin catchment together with the best available land use history and climate proxy records to determine the timing and possible causes of bench formation over the past 500 years. It was hypothesised that these bench features would provide a sedimentary archive that would reflect the post-European land use history in these catchments. A synthesis of the land use history of the Upper Burdekin will provide important context for the following three objectives. Firstly, histograms and probability density functions are derived from optically stimulated luminescence (OSL) dated bench samples to identify the timing of bench formation. From this analysis we can determine if the benches were formed pre or post European settlement. Secondly, we assess the stratigraphy and particle size composition of benches and estimate the proportion of fine sediment stored in bench features within these headwater river channels. Finally, the stratigraphy and OSL dates are used to provide insights into the relationship between land use history and bench sedimentation rate and timing. This study is unique in that it evaluates sediment storage in a relatively high energy tropical environment. Importantly, understanding how rivers have responded to both climate and land use change in the past, offers important insights into how rivers may respond in the future.

2. Study area

This study focuses on two tributaries in the Upper Burdekin

Table 1
Catchment characteristics of Keelbottom Creek and Fanning River as of 2012.

		Keelbottom	Fanning
Catchment area (km^2)		1627	1099
Geology[a]	Granite	27%	53%
	Basalt	0%	7%
	Sedimentary	51%	30%
	Other	22%	11%
Average channel slope (channel)[b]		0.0031	0.0036
Max elevation (m)		593 m	548 m
Total channel length upstream (incl. tributaries) (km)		106 km	91 km
Mean annual rainfall (mm)[c]		785	706
Land use (as of 2012)		34% Grazing	70% Grazing
		65% Military	29% Military
		1% Mining/	1% Mining/
		Other	Other
Catchment shape[d]	Elongation ratio	0.49	0.46
	Circularity ratio	0.17	0.16
Gully Density (km/km^2)[e]		0.013	0.033
Current stocking rate[f] (1990–2012)		0.5 beast/km^2	~20 beast/km^2

[a] Derived from the 1: 100,000 Geoscience Australia Geology.
[b] Derived from the SRTM DEM.
[c] Long term average derived from Jarihani et al. (2017).
[d] Based on the methods described in Fryirs and Brierley (2013).
[e] Derived from Table 18 in Tindall et al. (2014) based on Lidar mapping in sub-sections of each catchment.
[f] Derived from Wilkinson et al. (2018) and Ash et al. (2000).

catchment: Keelbottom Creek and Fanning River sub-catchments (Fig. 1). These catchments were chosen as (i) they are among the wetter of the Upper Burdekin catchments (Jarihani et al., 2017), and are known to have considerable influence on sediment delivery to the Burdekin river mouth (Maher et al., 2009); and (ii) they have a diverse range of contemporary land uses and histories which allows us to investigate the influence of land use on the sedimentary record. These study catchments represent first and second order headwater streams. A summary of the key characteristics of each of these catchments in given in Table 1.

2.1. Biophysical setting

The Burdekin catchment in Queensland, Australia, is the largest contributor of sediment to the GBR lagoon (Kroon et al., 2012) (Fig. 1). The Upper Burdekin River drains an area of ~36,000 km^2, and is a large
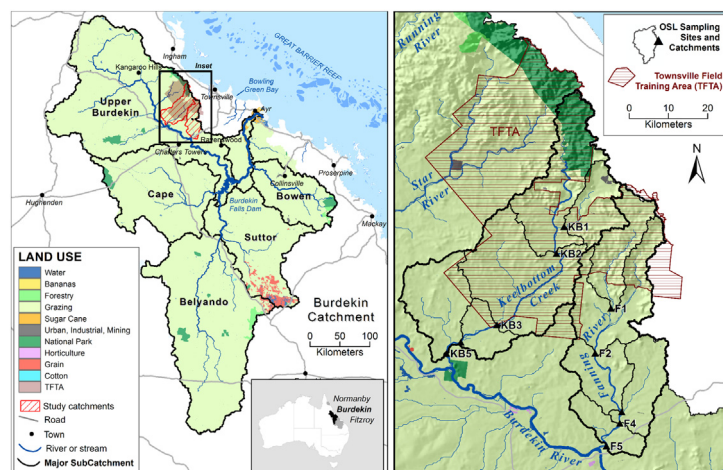

Fig. 1. Location of the five sampling sites along Keelbottom Creek (KB1–KB5) and Fanning River (F1–F5) catchments within the Upper Burdekin catchment.

incised channel with little or no floodplain. Bench development is common and ubiquitous along the Upper Burdekin River and its tributaries (Fielding and Alexander, 1996; Fielding et al., 1997).

The Upper Burdekin catchment is bound by the Coastal (or Hervey's) Range in the East, and the younger basalt plateau in the west (part of the Great Dividing Range). The modern Upper Burdekin river is incised into Palaeozoic bedrock (Wohl, 1992) and is primarily underlain by remnants of sedimentary basins which are composed of volcanic and sedimentary rocks ranging from Silurian to Tertiary in age (Ciesiolka, 1976). The Keelbottom and Fanning River catchments drain the high relief areas in the east which were formed from igneous intrusions in the north east of the catchment. Texture-contrast soils, which are generally found on the granitic landforms, are a dominant soil group in the Upper Burdekin catchment (Ciesiolka, 1976; Rogers et al., 1999). Within the uniform textured soils, sands and loams composed of the remnants of granite, quartzose and sandstone contribute the sediment load of the streams (Ciesiolka, 1976). The channel fill deposits of the Upper Burdekin main channel and tributaries are comprised of thick, laterally extensive bodies of well-sorted, gravelly to very coarse-grained sand, with discrete beds of gravel which are punctuated by discontinuous mud layers (Fielding and Alexander, 1996). There are no classic floodplain features within either Keelbottom Creek or the Fanning River as they are largely incised headwater channels.

The vegetation in the Upper Burdekin varies with rainfall gradient and soil type, but is dominated by Eucalypt savanna woodland overlaying a layer of tropical grasses. The trees are a mixture of ironbark/bloodwood communities (e.g. narrow-leafed ironbark, *Eucalyptus crebra*, and red bloodwood, *Corymbia erythrophloia*) and shrubby species (e.g. currant bush, *Carissa ovata*, and false sandalwood, *Eremophila mitchellii*). The grasses are a mixture of native species, but increasingly the introduced but naturalised stoloniferous grass Indian Couch (*Bothriocloa pertusa*) dominates pasture composition.

The climate in the Upper Burdekin ranges from tropical sub-humid adjacent to the Coastal Range near Keelbottom Creek and Fanning River (Köppen-Geiger type Cwa), to semi-arid in the western side of the catchment (Köppen-Geiger type BSh) (Peel et al., 2007). The annual rainfall varies between 560 and 2300 mm/yr in the Upper Burdekin and on average is ~710 mm/yr (1889–2016; based on July – June water year). Mean annual runoff (1948–2016) is 130 mm (runoff ratio of 18%) and the average annual potential evaporation of the catchment is 1734 mm (Jarihani et al., 2017). The Upper Burdekin only represents ~28% of the catchment area, but generates ~43% of the mean annual discharge (Maher et al., 2009), and the flood discharge record of the Burdekin places it alongside some of the world's major rivers (Fielding and Alexander, 1996).

Recent studies using annual luminescent lines derived from inner-shelf coral cores were used to reconstruct the Burdekin River flow from 1648 to 2011 (Lough et al., 2015). The reconstruction showed a general shift to higher flows, and increased runoff variability, in the latter half of the nineteenth century (see Fig. 7). The reconstruction also highlighted that the frequency of high flow events has increased from 1 in every 20 years prior to European Settlement (1748–1847) to 1 in every 6 years (1948–2011), and three of the most extreme events over the ~360 year record have occurred since 1974. This shift occurred from around ~1850, coincident with early European settlement in the region. Trend analysis of recent stream-flow records (1920–2007) in the Upper Burdekin suggests that some of this increased variability may be the result of decreases in base-flow following vegetation clearing, and increased event storm flow during large rainfall events (Peña-Arancibia et al., 2012). However, definitively attributing changes in stream flow to land use change is difficult in catchments dominated by storm driven runoff (Jarihani et al., 2017).

2.2. Erosion history in the Burdekin catchment

Coral geochemical records from Havannah Island (McCulloch et al., 2003a) and Magnetic Island (Lewis et al., 2007) show increased terrestrial influence from the Burdekin River between ~1854 and 1870. Sediment accumulation rates measured using OSL and radiocarbon dating of sediment cores measured an increase in sediment accumulation in Bowling Green Bay from 0.9 mm/year (540 to 210 years BP) to 9.4 mm/year over the past ~200 years (Lewis et al., 2014b). Whilst this later study measures sediment accumulation rather than sediment load, it provides evidence of the change in sediment delivery from the Burdekin Catchment to the GBR Lagoon since ~1850.

Several studies have highlighted the dominance of the Upper Burdekin sub-catchment as a major source of runoff and sediment yield to the Burdekin River mouth using mineral magnetics (Maher et al., 2009), geochemical tracing (Furuichi et al., 2016) and clay minerology (Bainbridge et al., 2016). In addition to this work, terrestrial cosmogenic nuclides ([10]Be) demonstrated strong agreement between measured nuclide concentrations in the Upper Burdekin and the river sediments at the mouth of the Burdekin River, suggesting that prior to the construction of the Burdekin Falls Dam, the Upper Burdekin sub-catchment dominated end of catchment sediment flux (Croke et al., 2015). The Upper Burdekin also dominates both overall runoff (Bainbridge et al., 2014) and is second only to the Bowen basin in terms of both increased anthropogenic sediment yield (Bartley et al., 2015) and fine sediment yield (Bainbridge et al., 2016). Bartley et al. (2015) estimated that, on average, current sediment yields in the Upper Burdekin have increased ~3.6 ± 0.5 times over long term (~100 to > 10,000 yr) erosion rates.

Fallout radionuclide studies using ^{137}Cs and ^{210}Pb in the Keelbottom catchment and sub-basins of the Fanning catchment suggest that > 70% of the sediment yield from these catchments is derived from subsurface sources (i.e. gully or channel bank erosion) (Wilkinson et al., 2013). Tracing using [7]Be has also shown that features such as rills and scalds, that behave like sub-surface soils when using tracers, also contribute to end of catchment sediment loads (Hancock et al., 2014).

The identification of gully erosion as a major source of sediment lead to improved mapping of gully features across the Burdekin catchment (Tindall et al., 2014). The gully mapping identified very high concentrations of gullies near Charters Towers and Ravenswood, and along the length of the Upper Burdekin River (Fig. 2b). There are also high gully densities in parts of the Lower Suttor, Cape River and Bowen-Bogie sub-catchments. The gullies tend to occur in areas with high local relief and particular soil characteristics (e.g. high sodicity).

2.3. Land use history

The Upper Burdekin, Keelbottom and Fanning River catchments have had a diverse land use history that has included mining, grazing and more recently military training land. A summary timeline of the major historical events in the Upper Burdekin related to shifts in climate and land use are given in Fig. 5. Based on the historical analysis of major land use changes outlined below, four key time periods were approximated and is presented in Table 2. It is acknowledged that land management was undertaken by the Traditional Owners in the area prior to 1850, particularly with the use of fire (cf. Kershaw, 1986), however, this study is focused specifically on evaluating European land use change on sedimentation rates.

2.3.1. Mining

Gold was first discovered in the Upper Burdekin (on the Star and Cape Rivers) in ~1866, and by 1890, Charters Towers was the second largest town in Queensland (Roderick, 1981; Neal, 1984). The early mining was generally alluvial, and workings were often 60–70 ft deep. Deep shaft sinking on quartz reefs followed the alluvial mining. There was a significant increase in the annual output of gold in Charters
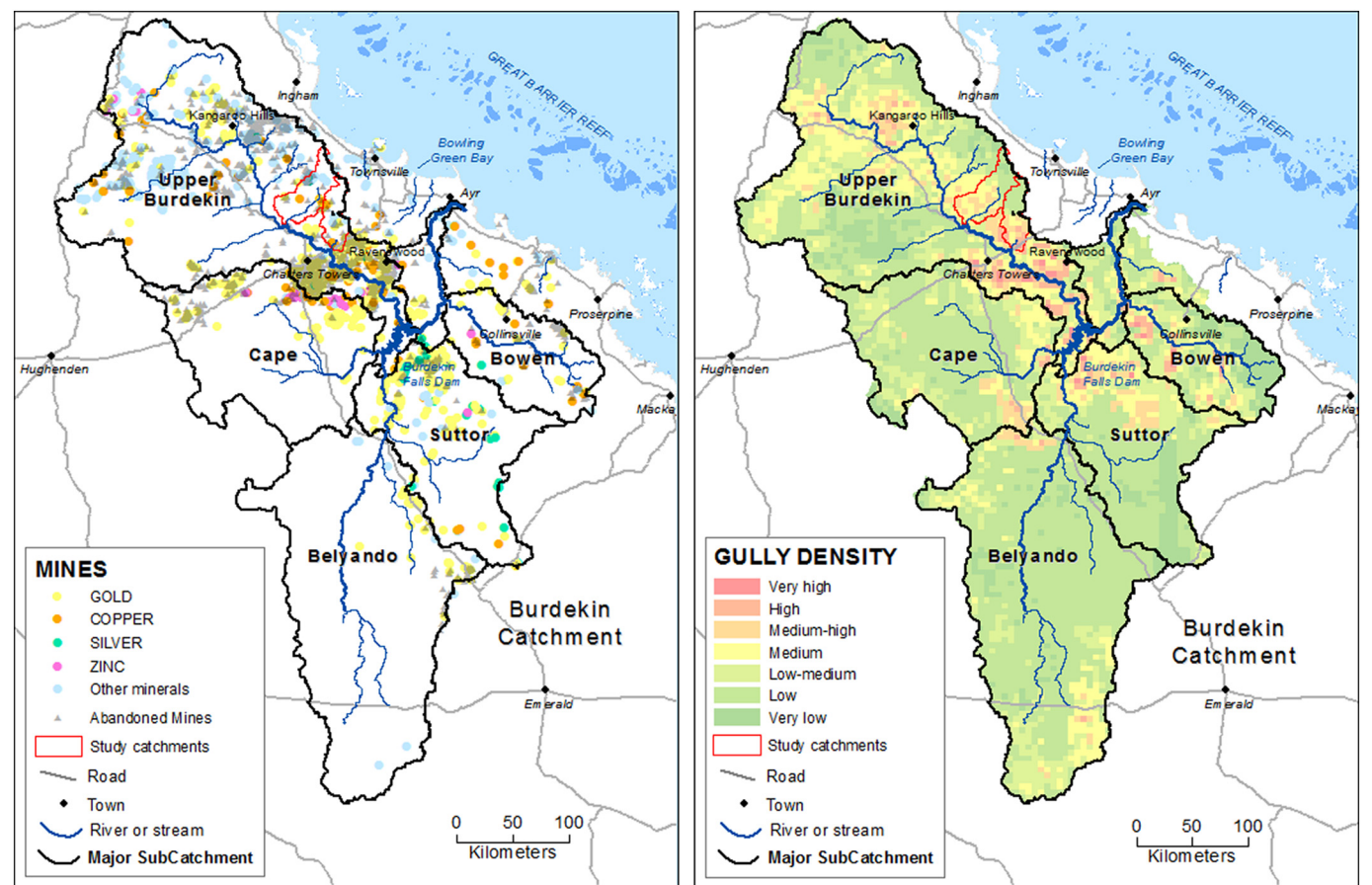
Fig. 2. (A) Current and legacy mining activity in the Burdekin Region. Source data: www.minesonlinemaps.business.qld.gov.au (WQIP, NQ Dry Tropics, 2016) and (B) 5 km gully presence mapping for the Burdekin catchment (Tindall et al., 2014).

Towers between 1896 and 1899 which was due entirely to the successful treatment by cyanide of the enormous heaps of old tailings (http://trove.nla.gov.au/newspaper/article/62893258).

In 1869 several miners travelled to Ravenswood and 'discovered two gullies rich in gold'. Initially, water was scarce at Ravenswood and the 'dirt was stacked in anticipation of rain'…'The following February brought floods, and the accumulated heaps of dirt were washed with much satisfaction by the miners' (Neal, 1984). In the late 1800s, many miners left the Charters Towers and Ravenswood area for the richer Goldfields on the Palmer River further north, however, sporadic reef, and then silver mining were continued from 1880 until ~1920. Mining of gold, silver, zinc, copper and other minerals occurred across numerous sites in the Burdekin (Fig. 2A). Up to 100 silver mining leases were active on Kangaroo Hills and Running River by 1891 (Neal, 1984). Alluvial mining for tin was important in the area depending on the wet seasons (as water was needed for processing) and prospecting continued to be carried out in the Kangaroo Hills area until 1960, 'with eleven mines still providing a living for gougers' (Neal, 1984). Both

Keelbottom Creek and Fanning Rivers were part of the area known as the Ravenswood Goldfield (Fig. 3). There were several mines in this area including Fanning and Far Fanning mines which were discovered in 1876, and ~220 oz of gold was found at these mine fields in the early years (~1880; Neal, 1984).

Mercury, which was used to extract gold from ore by the amalgamation process, was found in sediment cores in Bowling Green Bay, offshore from the Burdekin River, at maximum concentration levels of ~ 500 ppb, which is ~25 times the natural background concentration of ~20 ppb (Walker and Brunskill, 1997; Lewis et al., 2014b). Most mercury use around Charters Towers and Ravenswood was between 1870 and 1890. In the upper core layers, mercury has declined to concentrations of ~60 ppb which is a three-fold increase over pre-development levels. This sustained concentration may be due to (i) increased global atmospheric mercury; (ii) increased point source pollution; (iii) continued flushing of mercury from mine sites and remobilisation of stored sediments or (iv) mixing of sediments containing mercury from the initial large input in the late 1880s (Walker

Table 2
Four key time periods were approximated based on the historical analysis of major climate and land use changes.

|	Time period	Activity
1	Pre-1860	**No European anthropogenic land use** activity and pre-1860 climate shift
2	1860–1900	An **increase in rainfall-runoff activity** (as represented by flow anomalies) and **peak mining** activity in the area. Cattle are introduced, but in low numbers in the Upper Burdekin.
3	1900–1950	Reduction in mining activity with the **end of the Gold Rush** in 1924. Rainfall and runoff remains higher than pre-1860. Cattle numbers increase following WWII.
4	1950–2012	There was a **doubling of cattle numbers** in the Upper Burdekin between 1961 and 1978. The TFTA was established in the Keelbottom Creek catchment. The year 2012 represents the year the OSL samples were collected.
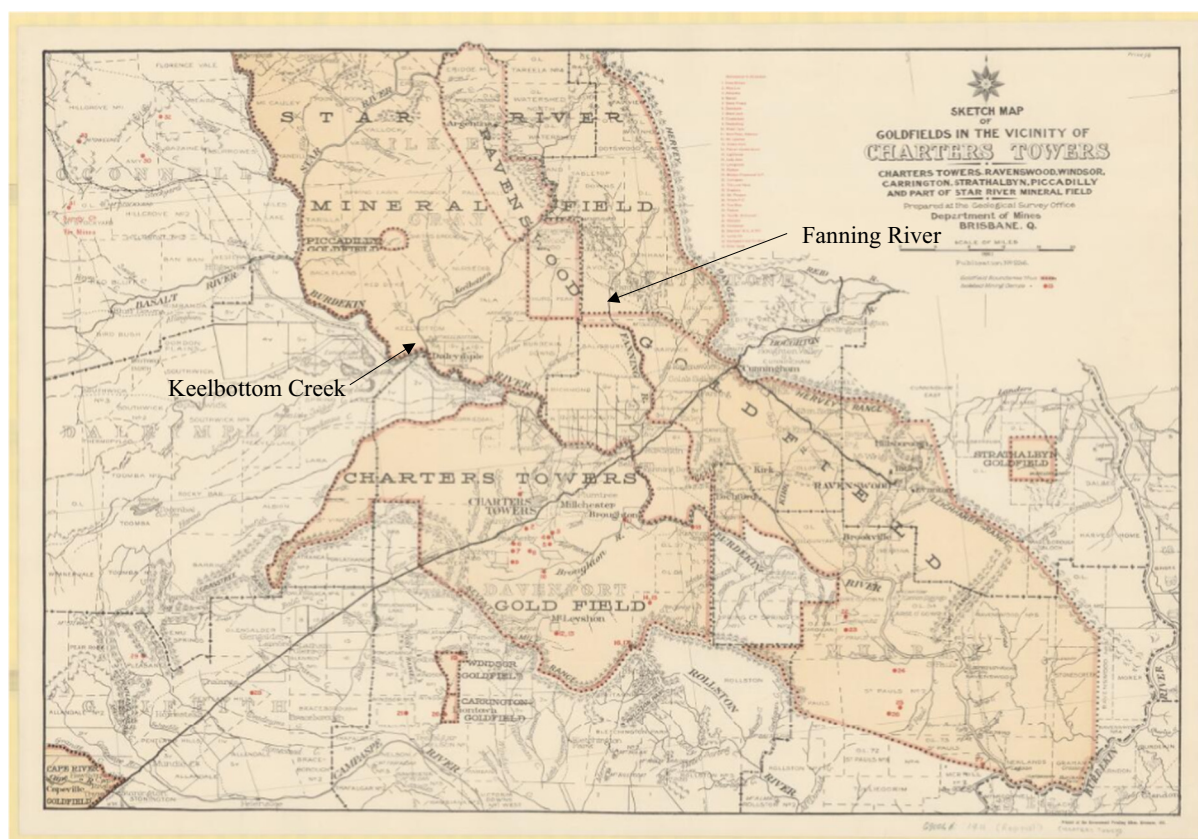
Fig. 3. Map of the Goldfields in the vicinity of Charters Towers (1911). Red dots mark the isolated mining camps. Source: Geological Survey of Queensland (Dept. of Mines), Queensland State Library Brisbane. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Brunskill, 1997).

2.3.2. Grazing

The establishment of the town of Bowen in 1861 provided a base for the pastoral development of north Queensland (Roderick, 1981). By 1880, cattle numbers in greater north Queensland were estimated at 450,000 (Neal, 1984). In the Burdekin catchment, cattle numbers have steadily increased from 0.05 million in 1860 to ~1.4 million in 2010–11, with cattle numbers highest in the Belyando, Cape, Bowen and Suttor sub-catchments between 1860 and 1950 (Lewis et al., 2007), however, Irvine (2016) suggests that these may be an over-estimate. The cattle numbers in the Upper Burdekin were relatively low during this time period, and in fact Lewis et al. (2007) states that in 1860 only 2 sheep and 121 cattle were grazed in the Upper Burdekin compared to ~300,000 sheep and ~13,000 cattle in the Belyando sub-catchment.

In the Fanning River catchment, a lease for the Fanning River Station was originally taken up in 1861, but was then abandoned in the late 1870s due to drought (Neal, 1984). A tick plague also wiped out a lot of cattle in the north in ~1895 and Fanning River station was depleted to one quarter of its stock (Neal, 1984).

Dotswood Station, in the Keelbottom catchment, was established in the 1860s. Dotswood Station was initially quite successful as they supplied beef to the local miners around the Star and Lynd Rivers and Mt. Molloy (Cohen, 1988). It was one of the first stations to treat cattle (sell to slaughter) in Townsville, with ~500 head being processed in ~1866 (May, 1984). However, Dotswood station was also impacted by the drought and tick plague and it went bankrupt in the mid 1890s (Cohen, 1988). Between 1916 and 1920, the State Government in Queensland purchased a number of cattle stations, including Dotswood Station in Keelbottom Creek. Cattle numbers at Dotswood were estimated to be ~14,400 between 1916 and 1920 (Cohen, 1988). Given

that Dotswood Station was approximately 1550 km², this equates to stocking densities of ~9 beasts per km². This stocking rate is within the range of estimates for other parts of central Queensland circa 1895 (~0.1 beast per hectare or 10 beasts per km²) (Irvine, 2016). However, the world slump in cattle prices in 1920 devastated Queensland's beef industry and virtually signalled the end for the State owned Stations (Cohen, 1988).

The demand for beef in the Second World War then assisted the recovery of the cattle industry (Neal, 1984). Methods for achieving greater production occurred following WWII and included a reduction in property size, increased fencing and paddock sub-division, tree ring barking, fertilised improved pastures, introduced pastures and legumes and supplementary feeding. The Upper Burdekin had much lower cattle numbers until after WWII when they increased to ~0.5 million, and represented the largest cattle numbers in the Burdekin from 1950 onwards (Mortiss, 1995; Lewis et al., 2007).

Grazing has occurred in the open woodlands of north Queensland for ~120 years, and although botanical shifts occurred, there was relatively little degradation during the first 100 years (Gardener et al., 1990). The main limitation to cattle production was poor quality herbage, and stocking rates were low to enable maximum selection of the most nutritious plants. In the 1970s there was a shift in cattle genotypes from the British (*Bos taurus*) breeds to the zebu (*Bos indicus*) cattle. The *B. indicus* cattle had much greater breeder survival rates, greater tick resistance, and greater tolerance to heat stress, and this switch in genotype is considered to have contributed significantly to the grazing pressure in the area (Gardener et al., 1990; McKeon et al., 2004). The result of the change in cattle breeds, along with the use of supplements, was reduced animal mortality, increased calving and more rapid growth rates. These changes, along with low beef prices in the 1970s resulted in a doubling of cattle numbers between 1961 and 1978.
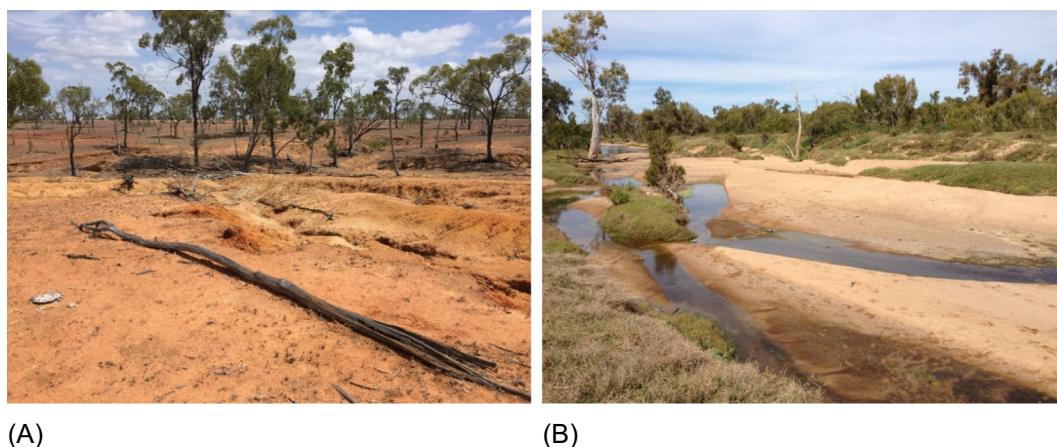
(A)   (B)

Fig. 4. (A) Typical over-grazed landscape in the Fanning River area and (B) the slugs of sand moving along the main channel of Fanning River. Photos taken in ~2012.

Obtaining exact numbers for stocking rates, density and distribution in the Upper Burdekin is extremely difficult. Previous attempts at deriving stock numbers suggest that there are large differences in cattle numbers presented by the Australian Bureau of Statistics (ABS) and the Dalrymple Landcare Group (Mortiss, 1995; McKeon et al., 2004). Stocking rates were estimated to be ~5.7 beasts/km^2 in the 1950s, which increased to ~12.3 beasts/km^2 prior to the 1970s (Mortiss, 1995), although this would have varied considerably within and between properties. Anecdotal evidence also suggests that cattle congregated along stream lines to access water prior to 1970s after which time there was an increased use of off-stream stock watering points.

Studies in the 1970s suggested that ~12.4% of the Upper Burdekin catchment suffered from soil erosion (see Fig. 4A), and "the natural erosion processes occurring in the area due to its geology and pedology have been accelerated by the activities of man. These activities include production of beef cattle, and provision of rural roads, the latter in particular being instrumental in concentrating runoff waters with gully erosion being the result" (Burdekin Project Committee, 1976). Grazing, combined with the legacy of mining, has resulted in sediment bedload waves within the main river channels on Fanning River (see Fig. 4B) and to a lesser extent on Keelbottom Creek; but the current land condition is considerably better in Keelbottom Creek than in Fanning River.

2.3.3. Defence lands

In 1967, the Department of Defence initially purchased 50,000 ha of grazing land in the Hervey's Range area, and then they acquired Dotswood Station in 1989. This area is now known as the Townsville Field Training Area (TFTA) (see Fig. 1). As part of the purchase agreement, grazing continued at Dotswood Station until July 2000. Since then, cattle were largely removed to allow for military training activities to take place, and there has been limited grazing by cattle and feral horses since this time. Current stocking rates in the TFTA are extremely low, and estimated to be ~0.5 head/km^2 (Wilkinson et al., 2018).

Anecdotal evidence presented in Ash et al. (2000) showed that floral surveys carried out in the TFTA area in the late 1960s and early 1970s identified similar plant communities to those found in 1998. The results of more recent surveys showed that the condition of the ground layer vegetation had improved since 1998 (Wilkinson et al., 2018). This contrasts with properties in the Fanning River catchment that had a dramatic shift in pasture composition (from native grasses to the exotic *Bothriochloa pertusa*) between 1979 and 1988 (Gardener et al., 1990; Bartley et al., 2014b).

3. Methods

There were five sampling sites located along both Keelbottom (K1-K5) and Fanning Rivers (F1–F5). Bench deposits on Keelbottom and Fanning Rivers were sampled at roughly equidistant locations down each catchment (Fig. 1). Benches were identified at each site and were sampled for morphology, stratigraphy and particle size according to the methods outlined below. Several OSL samples were collected at varying depths at each bench site.

3.1. OSL sampling

Targeted OSL sampling was confined to dating recognisable coarse-grained sand deposits differentiated within the bench by changes in stratigraphy and sedimentology. These deposits were often preserved as recognisable flood couplets with the bounded coarse and fine-grained deposits reflecting a reduction in flood discharge as the hydrograph changes. Although OSL samples were targeted at medium to coarse sand units, subsequent particle size analysis determined that in a few cases finer sand layers were sampled. At each of the bench sites, ~5 cm diameter steel tubes were inserted horizontally into the cleaned bench faces at locations marking notable changes in stratigraphy such as either particle size changes or evidence of erosional contacts between units (e.g. Fig. 6). Where erosional contacts were observed, the record of flood timing presented here is best interpreted as a minimum and is likely to reflect a discontinuous flood history. Up to four OSL samples were collected from each site depending on the bench height and stratigraphy. The OSL samples were prepared following standard procedures (Aitken, 1998). Pure extracts of 180–212 μm quartz grains were isolated, and treatments were applied to remove contaminant clays, carbonates, feldspars, organics, heavy minerals and acid soluble fluorides and samples were etched in 48% hydrofluoric acid.

Single-grain equivalent dose (D_e) values were determined using the modified single aliquot-regenerative dose (SAR) protocol of Olley et al. (2004) and Risø instrumentation described therein, in combination with the acceptance/rejection criteria provided in Pietsch (2009). Grains were rejected if either of the second or third Test Dose signals varied in sensitivity from the first Test Dose (associated with the Natural Dose) by > 20%.

Burial doses were calculated using the unlogged minimum age model of Arnold et al. (2009) and the PDF$_{Gaussian}$ approach of Pietsch (2009). The central age model (CAM) was used to identify the level of over-dispersion within the single grain dose distributions. Over-dispersion is recognized as the spread in the data above that which would be expected based on just the measurement uncertainties of the individual single grain dose values. The most common cause of over-

dispersion is partial bleaching, where only a (usually small) component of the grains was fully bleached by sunlight prior to burial. In these cases the 'minimum age model' (MAM) isolates the lowest dose component for age estimation.

Radionuclide activity concentrations were determined using high-resolution gamma spectrometry with dose rates calculated using the conversion factors of Stokes et al. (2003) and β-attenuation factors taken from Mejdahl (1979). Cosmic dose rates were calculated from Prescott and Hutton (1994) and long term water contents were estimated from measured water contents. Concentrations of ^{238}U, ^{226}Ra and ^{210}Pb are consistent with secular equilibrium in most samples. The minor secular disequilibrium observed in some samples is not sufficient to result in the calculation of an age significantly different from that which would result from assuming equilibrium conditions to have persisted through-out the burial period. Hence, for simplicity, the ages have been calculated using the as-measured radionuclide contents.

3.2. OSL sample distributions

To help visualise the distribution of events over time, two approaches were used. Frequency histograms for the OSL dates were developed for each catchment using a bin width of 20 years. This method allows us to broadly identify patterns in fluvial activity and provides an approximate estimation of the overall fluvial age distribution (Croke et al., 2011). However, given not all flood couplets were dated, a more robust method for analysing the distribution of flood deposits over time uses estimates of the probability density function (PDF). The probability density function of OSL dates provides information about the relative frequency of individual dates, and their associated uncertainty, relative to all samples collected in each catchment. An estimate of the relative frequency of an event between any two dates will be the area under the curve between those dates, according to Eq. (1) (Croke et al., 2016). Periods with greater depositional activity, as marked by an increase in dated units with lower uncertainty, will have greater area under the curve than periods with low activity as marked by fewer dates.

$$P(t_1 \leq t \leq t_2) = \int_{t1}^{t2} PDF(t)dt \tag{1}$$

An adaptive kernel density estimation (AKDE) was used to provide a smooth and continuous estimate of the PDF and was done in R (R Core Team, 2015) using the provenance package (Vermeesch et al., 2016). The Kernel function is a symmetrical distribution that integrates to 1. For a set of *n* measurements of OSL dates x_i ($i = 1 \rightarrow$ n), the KDE estimator is calculated according to Eq. (2). Where K(.) is the kernel and *h* is the bandwidth. The AKDE uses time-varying bandwidths (h) which allows for some consideration of the varying distribution of dates over time both as a product of sampling design and sediment preservation issues over time (Croke et al., 2016). Bandwidths are wider when data are sparse and narrower when observations are dense. In this study, the initial bandwidth (h) was selected using least-squares cross-validation (Hall, 1983) which was 67.6 years in Keelbottom, and 14.2 years for the Fanning catchment.

$$KDE(x) = \frac{1}{nh} \sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \tag{2}$$

3.3. Hydrology, morphology, stratigraphy and particle size of benches

Cross-sectional surveys of the channel were undertaken at each site using a Sokkia SET510 Total Station. Long profiles of bed slope were measured for ~100 m up and downstream of each cross-section. Maximum flow series data for an existing gauging station on Keelbottom Creek, and a discontinued gauge site on Fanning River, were used to estimate flow recurrence (Queensland Government Water Monitoring Data portal). A common time period between 1974 and

1993 was used to approximate the recurrence of the 1 in 10 year event at each site, using the method described by Grayson et al. (1996) for extending flow records to ungauged catchments (Bartley et al., 2008). This recurrence interval was anticipated to represent the flow for bench inundation and development. The more common 1 in 1.58 recurrence interval for estimating channel forming discharges was not considered appropriate for these semi-arid systems with large and infrequent rainfall and runoff events (Rustomji et al., 2009). To estimate stage height, the discharge data were then modelled in HEC-RAS 4.1 using the surveyed cross-sections, channel slope and estimates of Manning's n (~0.03) (Chow, 1959).

At each bench site the bench stratigraphy was described using hand-dug, soil pits to a depth of ~3 m, and samples were collected for particle size analysis at, and between, each OSL sample location point. The particles were dry sieved using 13 nested sieves between 63 μm and 4.0 mm. The particle size data were then grouped into gravel-cobble (> 2 mm), medium to coarse sand (500 μm–2 mm), fine sand (63–500 μm) and silt and clay (< 63 μm) for each bench using Gradistat software (Blott and Pye, 2001).

To determine the volume of sediment stored in each reach, the mean bench width and height (at the basal OSL age) were calculated and multiplied by the upstream bench length which was calculated as the sum of the stream length between each reach based on the 1:250,000 Shuttle Radar Topography Mission (SRTM) Digital Elevation model (DEM). All upstream tributaries identified on the SRTM DEM were included. This storage assumes that the bench morphology at each cross-section is representative of the length of bench upstream to the next cross-section. This assumption is considered reasonable based on field inspection and aerial photo surveys. LiDAR data was not available for the entirety of these catchments, however, visual assessments of bench features where LiDAR was present, confirmed this assumption to be reasonable. The volume calculations were then multiplied by the bulk density of unconsolidated sediment, which is estimated to be ~1.8 t/m³ (after Pietsch et al., 2015). To calculate the % of fine (silt and clay) sediment stored, the total volume of sediment was multiplied by the proportion of silt and clay in each stratigraphic unit.

3.4. Sedimentation rates

Sedimentation rates were derived by dividing the vertical height of the sedimentary unit by the basal OSL age for that unit. The sedimentation rates were then grouped according to (i) their sampling location (e.g. KB1–5; F1–5; Fig. 1) and (ii) the land use change time periods outlined in Table 2. As noted previously, some within-bench erosion almost certainly occurred between the major flood couplets sampled for OSL dating. The method of calculating and expressing sedimentation rates in this study is unable to accurately reflect the punctuated flood history that is likely to have prevailed. Expressing sedimentation as a constant annual rate allows comparison across space and time but should be considered as a minimum.

4. Results

4.1. OSL ages

A total of 28 OSL samples were collected across the two catchments (Table 3). The dates of sediment deposition (based on OSL ages) measured on Keelbottom Creek range from the year 1656 ± 42 to 2012 ± 3, and on the Fanning River they are younger and range from 1873 ± 13 to 2012 ± 3 (Fig. 7). Estimates of the PDF (AKDE) suggest that the last phase of bench formation had started prior to European Settlement in Keelbottom Creek and immediately after European Settlement on the Fanning River. There were several OSL samples collected from the Fanning River dated to between 1920 and 1960 (n = 6), as illustrated by the histogram, however, no OSL samples from Keelbottom Creek coincided with this time period (Fig. 7). There were also very few

Table 3

OSL ages (with uncertainties) rounded to the nearest 1 year and radionuclide concentrations for the bench sites on Keelbottom Creek and Fanning River. All radionuclide values are in Bq kg^{-1}.

Catchment	Site #	Sample depth (cm)	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{40}K	^{137}Cs	OSL age (years prior to 2012)	Deposition year (CE)
Keelbottom	1	60	27.54 ± 8.05	13.75 ± 1.72	28.49 ± 8.46	25.09 ± 1.40	714.66 ± 27.90	0 ± 0.30	0 ± 3	2012 ± 3
		185	23.45 ± 5.88	22.09 ± 2.43	19.29 ± 6.00	26.61 ± 1.72	876.39 ± 59.80	0 ± 0.19	155 ± 14	1857 ± 14
	2	30	23.98 ± 9.12	17.68 ± 2.52	24.25 ± 9.20	24.38 ± 2.02	728.03 ± 52.60	0 ± 0.39	16 ± 3	1996 ± 3
		105	43.04 ± 6.33	30.33 ± 3.00	32.49 ± 5.15	44.86 ± 2.81	703.21 ± 47.26	4.44 ± 0.69	47 ± 5	1965 ± 5
	3	40	34.89 ± 4.47	28.52 ± 2.58	34.44 ± 6.31	30.40 ± 1.51	574.89 ± 26.03	1.00 ± 0.49	45 ± 5	1967 ± 5
		190	49.49 ± 8.04	29.70 ± 2.61	26.45 ± 5.41	39.26 ± 1.81	620.76 ± 24.58	0.78 ± 0.29	100 ± 12	1912 ± 12
	4	80	21.00 ± 4.00	29.00 ± 5.00	19.00 ± 5.00	20.19 ± 0.98	580.00 ± 26.00	0 ± 0.22	106 ± 14	1906 ± 14
		180	13.00 ± 4.00	21.00 ± 5.00	10.00 ± 4.00	13.75 ± 0.92	254.00 ± 21.00	0 ± 0.16	200 ± 21	1812 ± 21
	Left	150	46.00 ± 5.00	78.00 ± 10.00	39.00 ± 9.00	42.07 ± 1.99	680.00 ± 32.00	4.00 ± 1.00	50 ± 6	1962 ± 6
	5	65	17.51 ± 6.97	14.69 ± 1.69	15.20 ± 7.43	19.37 ± 1.07	471.94 ± 21.30	0 ± 0.28	94 ± 11	1918 ± 11
		220	25.67 ± 7.44	17.02 ± 2.17	22.98 ± 6.79	21.37 ± 1.13	569.82 ± 24.30	0 ± 0.28	141 ± 13	1871 ± 13
		315	13.71 ± 4.28	11.27 ± 1.39	15.37 ± 4.51	17.24 ± 1.35	217.47 ± 17.97	0 ± 0.15	356 ± 42	1656 ± 42
Fanning	1	45	25.66 ± 5.01	21.38 ± 1.87	19.53 ± 4.78	32.09 ± 1.47	895.85 ± 35.14	0 ± 0.22	77 ± 7	1935 ± 7
		120	18.66 ± 5.39	19.59 ± 2.22	16.77 ± 5.48	24.24 ± 1.59	927.74 ± 62.25	0 ± 0.19	99 ± 9	1913 ± 9
	2 (right)	30	33.21 ± 5.73	23.32 ± 2.29	35.88 ± 6.03	38.44 ± 2.43	666.60 ± 44.75	0.64 ± 0.31	0 ± 3	2012 ± 3
		77	36.95 ± 10.10	20.80 ± 2.24	29.66 ± 7.91	33.46 ± 1.64	602.40 ± 26.20	3.98 ± 1.21	7 ± 6	2005 ± 6
	2 (left)	75	11.00 ± 4.00	18.00 ± 4.00	8.00 ± 4.00	13.83 ± 1.07	975.00 ± 65.00	0 ± 0.14	80 ± 8	1932 ± 8
		125	18.00 ± 4.00	28.00 ± 4.00	13.00 ± 4.00	24.62 ± 1.57	1020.00 ± 68.00	0 ± 0.15	120 ± 11	1892 ± 11
	3	30	43.00 ± 10.00	53.00 ± 9.00	30.00 ± 7.00	42.09 ± 2.07	750.00 ± 34.00	5.00 ± 1.00	46 ± 7	1966 ± 7
		70	23.47 ± 7.01	16.49 ± 1.81	19.19 ± 5.67	26.27 ± 1.41	833.12 ± 37.95	0 ± 0.30	64 ± 6	1948 ± 6
		120	30.97 ± 5.95	16.27 ± 1.87	18.15 ± 6.07	31.26 ± 1.51	794.96 ± 34.83	0 ± 0.31	61 ± 6	1951 ± 6
	4	55	11.00 ± 4.00	17.00 ± 5.00	8.00 ± 5.00	17.89 ± 1.26	436.00 ± 32.00	0 ± 0.18	11 ± 4	2001 ± 4
		100	30.63 ± 15.84	14.83 ± 2.80	22.54 ± 16.07	34.02 ± 2.53	882.29 ± 64.47	0 ± 0.54	0 ± 5	2012 ± 5
		190	12.34 ± 6.93	6.22 ± 1.14	16.01 ± 18.35	12.82 ± 1.03	776.96 ± 53.18	0 ± 0.23	61 ± 6	1951 ± 6
	5	67	15.00 ± 6.00	15.00 ± 4.00	12.00 ± 5.00	11.61 ± 0.83	753.00 ± 33.00	0 ± 0.24	80 ± 8	1932 ± 8
		100	11.39 ± 6.64	8.61 ± 1.59	10.37 ± 9.35	23.30 ± 1.81	853.41 ± 60.06	0 ± 0.35	65 ± 8	1947 ± 8
		270	15.14 ± 4.95	6.72 ± 1.17	10.93 ± 4.47	8.74 ± 0.90	826.26 ± 33.80	0 ± 0.17	128 ± 15	1884 ± 15
		315	14.00 ± 4.00	18.00 ± 3.00	12.00 ± 4.00	14.54 ± 0.78	825.00 ± 35.00	0 ± 0.21	139 ± 13	1873 ± 13

samples dated to the 1970s from either catchment. It was not possible to correlate the OSL ages to a long term flood series in either catchment, as the flow gauges were either too high in the catchment, or the records too short and incomplete. As an alternative, the reconstructed Burdekin River flow (anomalies, deviation from the mean) based on coral core data from 1648 to 2011 were used (Lough et al., 2015) (Fig. 7).

4.1.1. OSL accuracy

All samples provided quartz suitable for single-grain OSL dating. All but one of the samples analysed here were over-dispersed, having σ_d values in the range 31% - 170%, i.e. considerably higher than the 15–20% generally regarded as typical of uniformly bleached samples.

A radial plot of OSL ages and relative errors shows the relatively homogenous age distributions between the two catchments (see Supplementary material). Relative standard errors are shown to be proportional to age, and range from 7.9 to 42.9% (Table 3), with one outlier of 86% for a sample dated as < 10 years old. The best measure of the quality on the ages used in this study is the degree of internal consistency. Across 28 samples distributed among 10 separate profiles, only one statistically significant age inversion occurred (at site 4). The dates of 2001 and 2012 are very young and were likely to be from a single flow event or mixture of several minor flow events over that decade.

The nuclear bomb fallout ^{137}Cs provides an independent check against the OSL ages. It also provides some insight into the potential sediment source. Caesium-137 was first detected in northern Australia in ~1959 (Wasson et al., 2010), however, it was present in the atmosphere prior to this period. Seven samples in this study contained ^{137}Cs, six of which were dated as being deposited after 1959 (see Table 3 and Supplementary material). One sample on Keelbottom Creek (site 2) contained ^{137}Cs, but was dated to ~1912 ± 12. This anomaly is likely to be explained by the movement of ^{137}Cs within the bench feature by the drawdown of clays into the bench following floodwater deposits or processes such as bioturbation (Rustomji and Pietsch, 2007); however, depth profiles were not explicitly measured to check for vertical

mobility of nuclides.

Wilkinson et al. (2013) determined that ^{137}Cs concentrations from top-soil sediments in the Upper Burdekin are, on average ~7.1 Bq kg^{-1} (25% CV), whereas sub-surface soils are ~0.27 Bq kg^{-1} (281% CV). This is consistent with ^{137}Cs concentrations measured in other parts of northern Australia (Wasson et al., 2010). Across the two catchments there were a total of 10 samples that were dated as being deposited after 1959. Of these 10 samples ~4 samples had ^{137}Cs concentrations ranging between 4 and 5 Bq kg^{-1}, and a further three samples had ^{137}Cs concentrations ranging between 0.5 and 1 Bq kg^{-1}. This suggests that although gully erosion is considered to dominate erosion in this landscape (Wilkinson et al., 2013), hillslope sheet erosion contributed sediment to the channel during this period. Because ^{137}Cs is only present in samples after 1959, it is not possible to determine what the dominant erosion process was prior to this period.

4.2. Hydraulics, morphology, stratigraphy and particle size of benches

The stratigraphy of benches in both Keelbottom and Fanning Rivers are presented in Fig. 8 and Fig. 9, respectively. The processing of the OSL dates with the sedimentology has determined that we have an incomplete stratigraphic record that represents sediments deposited post 1650. Evidence for this is shown in Fig. 7A, where there were considerably more large flow events that were not captured by dated samples in this study. However, the OSL samples collected still provide a reasonable representation of flow events and sedimentation rates associated with climate and land use shifts for these catchments.

With the exception of bench F5, all benches, in both catchments, are inundated by the 1 in 10 year annual recurrence interval (ARI) flow event (see Fig. 8 and Fig. 9). In many cases (e.g. KB 1, 3, 4 and 5), runoff events with lower flood frequency would deposit sediment on the bench surfaces.

The average sediment composition of the benches is presented in Fig. 10 (and in Supplementary material for individual sites). The sediment composition of the benches in both catchments was similar with
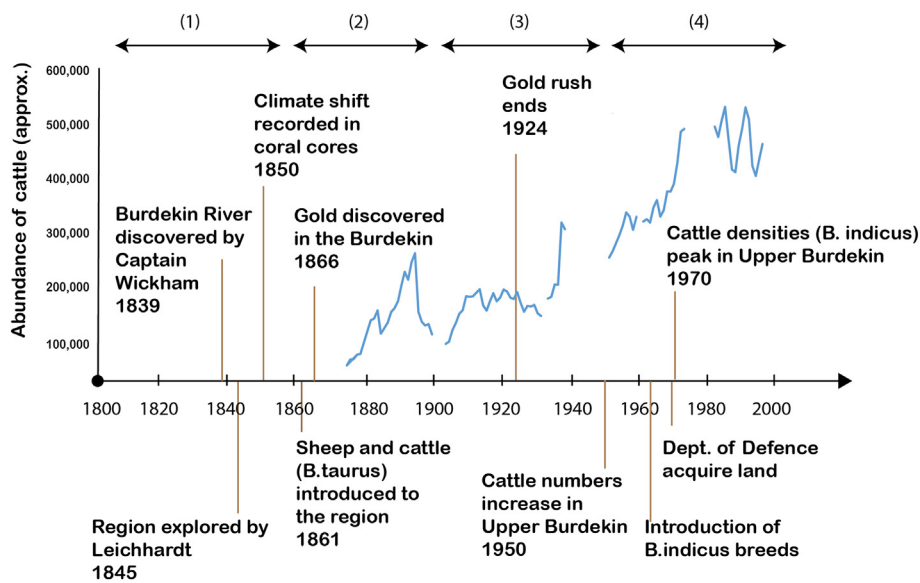
Fig. 5. Timeline of land use in the Upper Burdekin region (~36,000 km^2) with the approximated abundance of cattle shown in blue (after Lewis et al., 2007; Lewis et al., 2014a). The numbers at the top of the graphic represent the time periods represented in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
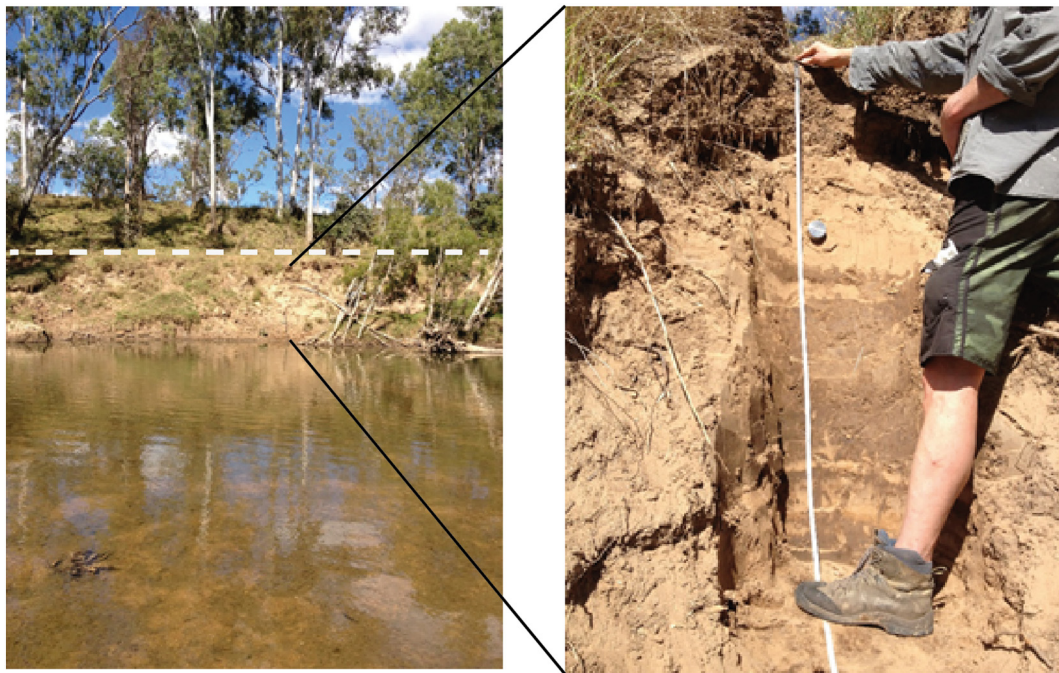

Fig. 6. An example of a typical bench deposit (KB5) with the white dashed line delineating the horizontal surface of the bench feature; (left) and the associated lamination and stratigraphy of sediment deposits (right).

gravel/cobble (~12–17%), medium to coarse sand (~50–55%) and fine sand (~29%). There were laminations of fine silt and clay within the deposits, but these represent, on average, only ~4% of the bench sediments.

The proportion of total sediment stored in each of the benches is given in Supplementary material (Table 6). The total amount of sediment stored is similar between Keelbottom Creek (~58,000 t yr^{-1}) and Fanning River (~61,000 t yr^{-1}), although the per unit stream length storage rates are slightly higher on Fanning River (0.29–1.42 t m^{-1} yr^{-1}) than on Keelbottom Creek (0.17–0.92 t m^{-1} yr^{-1}). The amount of sediment stored in Keelbottom Creek is ~36 t km^{-2} yr^{-1} and in Fanning River it is ~55 t km^{-2} yr^{-1}.

4.3. Sedimentation rates

Average bench sedimentation rates are higher and more variable on Fanning River (~2.5 cm yr^{-1}), compared to Keelbottom Creek (~1.6 cm yr^{-1}). The median sedimentation rates decline with progression down Keelbottom Creek, but the variability increases (Fig. 11). Conversely, the sedimentation rates increase travelling down Fanning River, with the median sedimentation rate peaking near site 4 (Fig. 11).

The bench sedimentation rates for each catchment were combined into four time periods based on the historical land use activities described in Table 2. Grouping the sedimentation rates across 50 year periods also reduced the influence of individual flood events (acknowledging that not all flood events were captured, so this helped reduce bias). It is acknowledged that when the data are grouped, there is little difference between the sites or time periods, however, there are
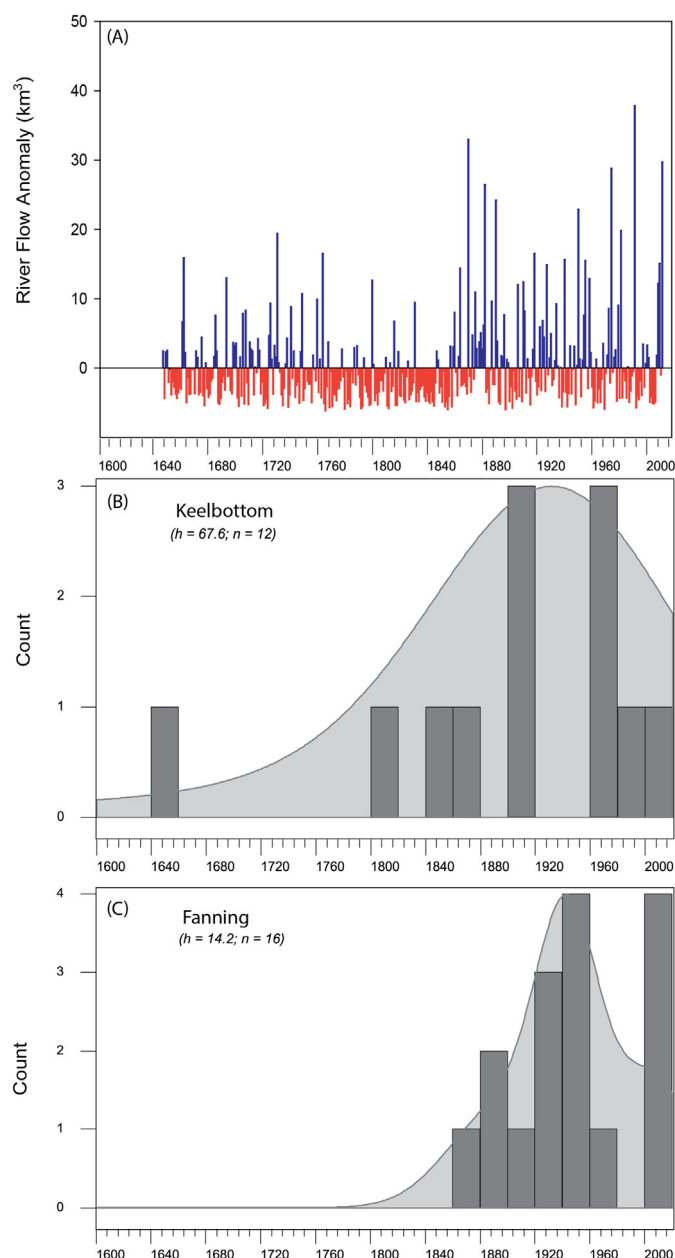
Fig. 7. (A) Reconstructed Burdekin River flow (anomalies, deviation from the mean) from 2011 to 1648 based on coral core data (Source: Lough et al., 2015); Frequency histogram and AKDE plots of the OSL data (based on deposition years) for (B) Keelbottom Creek; (C) Fanning River (Note: histogram bin widths were 20).

some variations in the sedimentation values which are worth noting.

Benches had started to form prior to 1860 on Keelbottom Creek and the highest rate of bench deposition was ~3.3 cm yr^{-1} which occurred between 1860 and 1900 (Fig. 12). Sedimentation rates then declined to an average of ~1.39 cm yr^{-1} between 1900 and 1950 before increasing again slightly to ~2.05 cm yr^{-1} between 1950 and 2000. When the average bench sedimentation rate for the high intensity cattle grazing period (1950–2012) is compared to the previous 50 year period (1900–1950) the bench sedimentation rate in Keelbottom Creek has increased ~1.5 fold. This is much lower than the ~4.3 fold change in sedimentation rate that occurred between the pre-1860 period, to the period between 1860 and 1900.

It appears that the first major episode of bench accumulation occurred in Fanning River between 1860 and 1900; there were no OSL

samples dated earlier than 1860 in the Fanning catchment. Bench sedimentation rates in the Fanning River changed from ~2.68 cm yr^{-1} between 1860 and 1900 and then declined to 1.6 cm yr^{-1} between 1900 and 1950. The sedimentation rates for the period after 1950 represent the highest rates for the available record (3.45 cm yr^{-1}). The average bench sedimentation rate for the high intensity cattle grazing period (1950–2012) is ~2.2 fold higher than the previous 50 year period (1900–1950).

5. Discussion

Bench features are considered to represent an archive of previous fluvial activity in a catchment, with many studies linking these features to post-European disturbance (Rustomji and Pietsch, 2007; Hughes et al., 2009; Portenga et al., 2016). However, it is also acknowledged bench features may represent changes to the sediment yield in a catchment due to natural fluctuations in climate and associated changes in rainfall and runoff (Wasson et al., 2010).

The Upper Burdekin catchment has been subject to multiple disturbances post-1860 which include extensive mining, cattle grazing and more recently military training activities. According to luminescent lines measured in coral cores, these land use changes coincided with a shift in the ENSO variability in the southwest Pacific Ocean, resulting in an increased frequency of high flow events in the Burdekin catchment around 1850 (Lough et al., 2015). The main aim of this study was to investigate the timing and formation of bench deposits in two catchments with variable land use histories, with the aim of explaining some of the complex interactions between climate, land use change and sediment storage in two tributaries of the Upper Burdekin catchment. All of these factors are known to have a large influence on sediment flux from the Burdekin catchment.

Most of the current debate around the need for improved land management in catchments draining to the GBR is focused on the current land uses (e.g. grazing), whereas legacy land uses (e.g. mining) and climate variability are largely ignored. This is one of the first studies that has provided a detailed description of the full range and timing of all land uses in the Upper Burdekin catchment since 1850 and has involved climate variability. It is considered important to understand the key drivers of erosion so that future remediation measures can be appropriately identified and implemented.

5.1. OSL dates and representation of the flow record

Given the size of the study catchments (~1000 km^2) the number of OSL samples collected in this study is modest, but comparable to other studies in the region (Hughes et al., 2009; Hughes and Croke, 2017; Nott, 2018). In this study there were only three OSL samples that date to pre 1860 (Fig. 13C). All of these were measured on Keelbottom Creek. Based on the reconstructed flow record (Fig. 13B), there were considerably more large flow events that were not captured by dated samples in our study. This could be because (a) the bench features formed prior to large flow events have subsequently been stripped and/or removed; or (b) these events were not evident or well preserved in the stratigraphic record and were not sampled for OSL analysis. In other parts of Australia, bench accretion and formation has been shown to occur in moderate flood events, with large flow events responsible for bench destruction and removal (Erskine and Warner, 1988). The 10 year ARI for bench formation in the study catchments is generally higher than for other studies (e.g. Hughes et al., 2009). This suggests there is a complex non-linear relationship between flow events and bench formation in these headwater catchments.

5.2. Morphology, stratigraphy and particle size

Fine (< 63 μm) sediment is of most interest to the health of the GBR (Bartley et al., 2014a), and is therefore the main focus of this

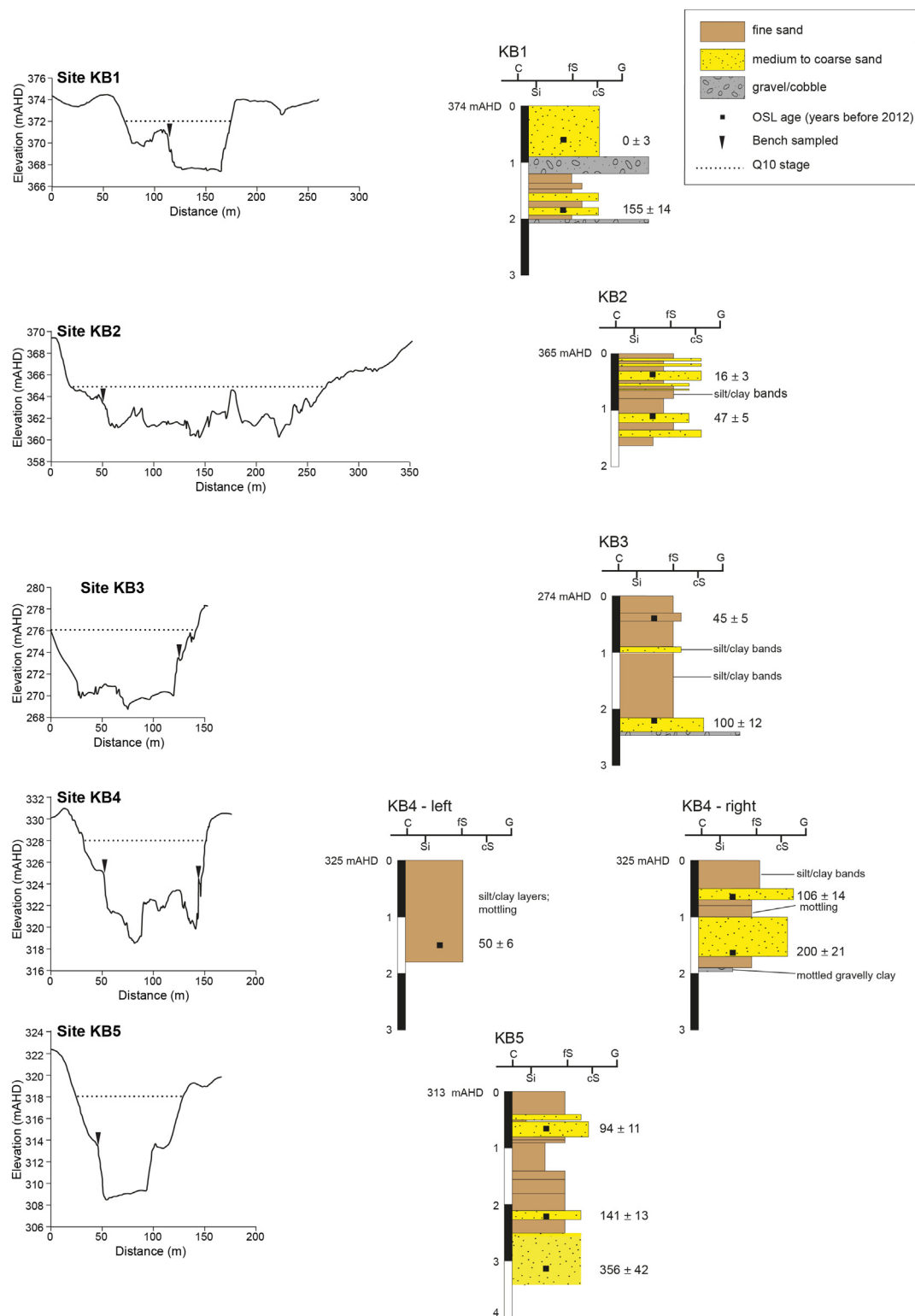**Fig. 8.** Stratigraphy and cross-sections measured on Keelbottom Creek. The approximated Q_{10} event stage is shown using a dashed line. Fine sediment ($< 63 \mu m$) recorded as small bands/laminations.

discussion. The bench deposits in both Keelbottom Creek and the Fanning River are dominated by fine and coarse sand, with fine (silt and clay) sediment ($< 63 \mu m$) generally representing between 2 and 8% (av. 4%) of the bench volume. Based on particle size analysis from colluvium that was exposed in the first order stream-bank sediments collected within the Fanning catchment, fine ($< 63 \mu m$) sediment represents ~25% of the eroded colluvium or parent material (Bartley et al., 2007). Using a value of 25% fine sediment composition for the parent material (to represent sediments derived from hillslope, gully and streambank erosion), this means that ~16% of the original fine material is stored in bench features (i.e. ~4% of the initial 25% of colluvium is stored in benches), and the remaining 84% of the fine material is transported out of these headwater streams. The proportion of fine ($< 63 \mu m$) sediment stored in benches in Keelbottom and
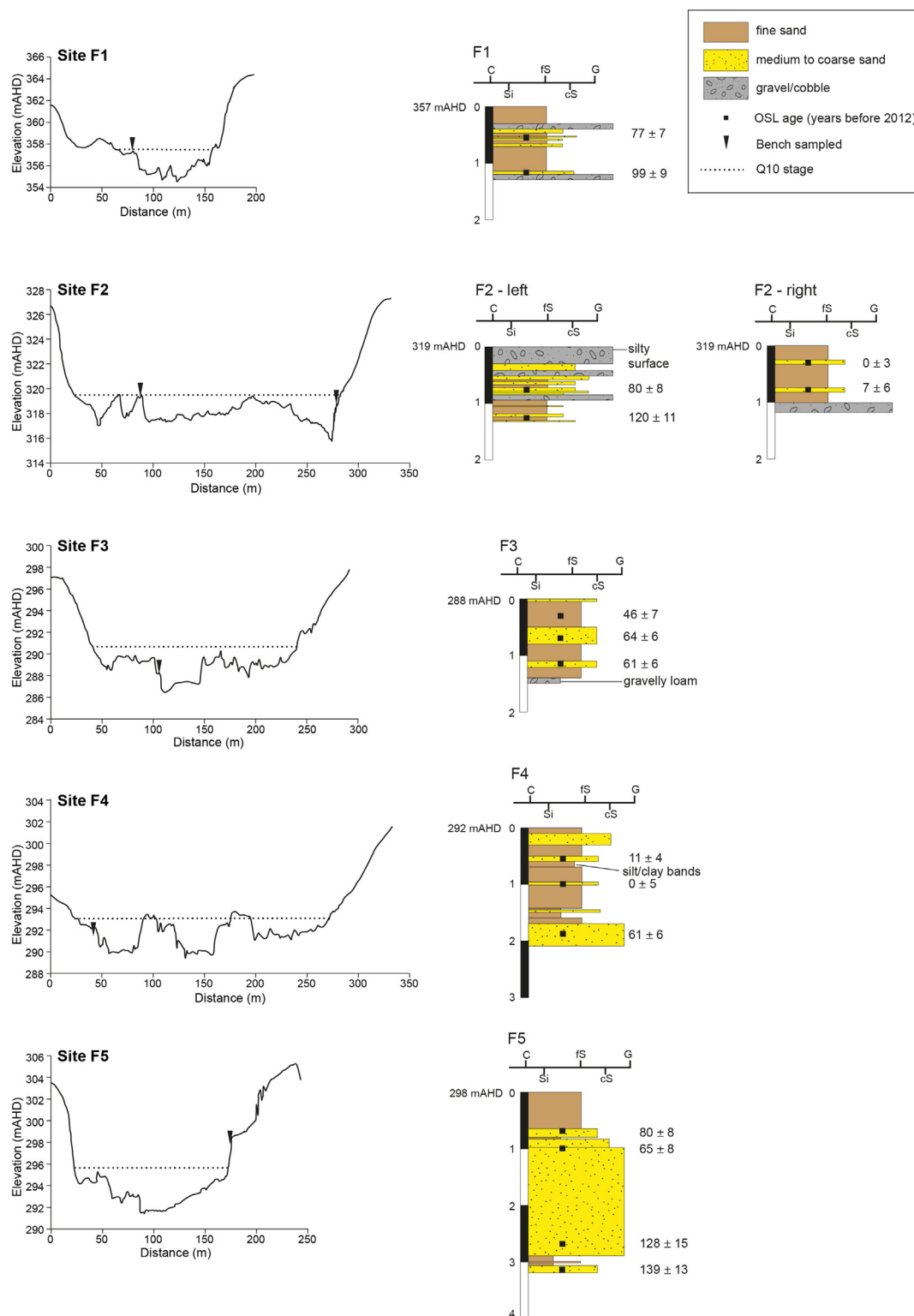
Fig. 9. Stratigraphy and cross-sections measured on Fanning River. The approximated Q_{10} event stage is shown using a dashed line. Fine sediment ($< 63\,\mu m$) recorded as small bands/laminations.

Fanning Rivers is slightly lower (but within range) of benches in the Normanby catchment, where the proportion of fine ($< 63\,\mu m$) sediment stored was between 16%- 55% (Pietsch et al., 2015). The lower fine sediment storage in this study is likely to be related to the higher rainfall-runoff co-efficients (Jarihani et al., 2017), higher channel slopes, and subsequently higher stream powers experienced in the Keelbottom and Fanning Rivers headwater systems. It is hypothesised

that benches, floodplains and footslopes in other, lower gradient, parts of the Burdekin catchment (e.g. Belyando sub-catchment) would have higher fine sediment storage.

5.3. Sedimentation rates

The sedimentation rates within and between the catchments were
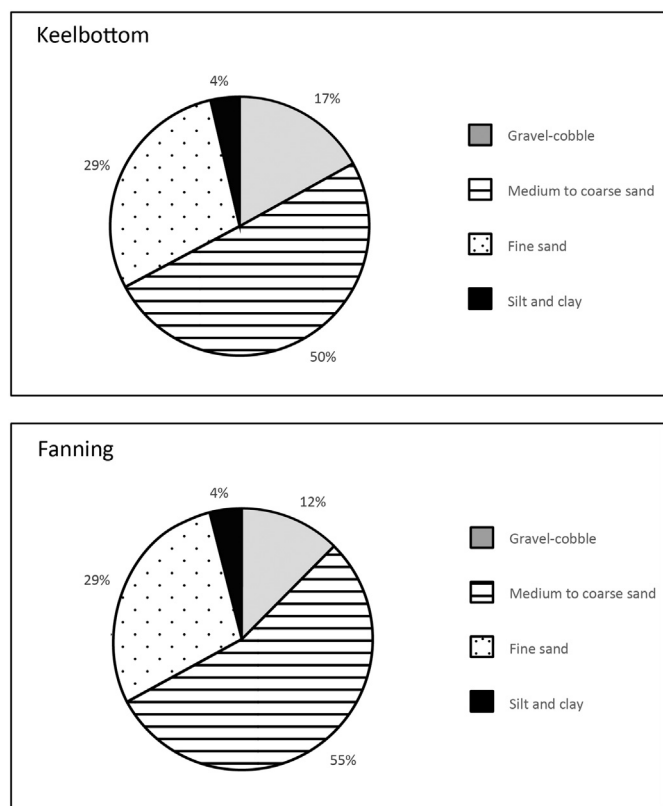
Fig. 10. Average proportion of gravel-cobble, medium-coarse sand, find sand and silt/clay for Keelbottom Creek and Fanning River. Particle size data for the individual bench sites available in Supplementary material.

variable; but there were some common trends. In both catchments, the mean and median bench sedimentation rates in the most recent time period (1950 to 2012) are higher than the period from 1900 to 1950. In both catchments the bench sedimentation rates in the period 1860–1900 were either higher, or not statistically different from the most recent period (1950–2012). The main difference between the catchments was that there was evidence of bench formation prior to 1860 on Keelbottom Creek, but not on Fanning River. The average bench sedimentation rates on Keelbottom (1.63 cm yr^{-1}) and Fanning River (2.49 cm yr^{-1}) were similar to the rates measured on benches in Theresa Creek in the Upper Fitzroy catchment (1.4 to 2.4 cm yr^{-1}) (Hughes et al., 2009) and on the Normanby River (1.3 to 2.3 cm yr^{-1}) (Pietsch et al., 2015). However, given the uncertainty regarding potential bench stripping or erosion by large events, the sedimentation

rate data indicate benches in both study catchments, regardless of recent differences in land management, are continuing to aggrade at an average of ~2 cm yr^{-1} (Keelbottom) to ~3.5 cm yr^{-1} (Fanning).

These results suggest that bench accretion and sedimentation was initiated prior to European settlement, but there was a considerable increase in sedimentation rate, ~4.3 fold in the case of Keelbottom Creek, in the 40 years between 1860 and 1900. There were several potential causes of this increase. Firstly, the increase in rainfall and runoff variability, revealed by coral cores, may have triggered an increase in erosion within the Keelbottom and Fanning River catchments (e.g. hillslope sheet erosion), and/or the increased discharge and associated stream powers may have re-worked within channel material (e.g. the channel bed and banks). The use of OSL data on its own cannot decipher the difference in these potential erosion sources. Secondly, the extensive occurrence of alluvial mining on the local gold fields (Fig. 3) may have triggered a wave of sediment into these rivers in the form of tailings or direct mining of alluvial areas. Thirdly, the introduction of cattle into the region, may have contributed to increased sedimentation resulting from reduced ground cover and coincident increases in hill-slope, gully and streambank erosion.

In both catchments, the period with the lowest average sedimentation rates was between 1900 and 1950. Even on Keelbottom Creek, the sedimentation rate during this period was not different to the pre-1860 rates. There is no obvious explanation for this reduced sedimentation, and this contrasts with other studies that identify sediment pulse peaks in the 1930s (McCloskey et al., 2016). It may represent a period of reduced sediment supply with the end of the Gold Rush and subdued or stable cattle numbers between 1900 and 1940 (Fig. 13), or as described previously, the incomplete stratigraphic record may have missed significant bench forming events during this period. Alternatively, there may have been partial stripping of the bench features during the 1946 flood which was the largest event on record for the Macrossan Bridge (Sellheim gauge) in the Upper Burdekin (data not shown).

Using a combination of erosion rates estimated from the application of cosmogenic nuclides (Croke et al., 2015) and contemporary erosion rates (Bainbridge et al., 2014) in the Upper Burdekin, Bartley et al. (2015) estimated that there has been a ~3.6 fold increase in erosion for the Upper Burdekin catchment. Assuming that the order of magnitude change has been similar for Keelbottom Creek and Fanning River, these bench sedimentation rates suggest that sediment storage has been roughly proportional to the changes in total sediment flux (approximately 1.5 to 4.3 fold), in these smaller headwater streams. These sedimentation rates are lower than the 8 to 10 fold increase in fine sediment accumulation found off-shore from the Burdekin River mouth over the last 210 years (Lewis et al., 2014b), however, this represents sediment delivery from the entire Burdekin. The Upper Burdekin would

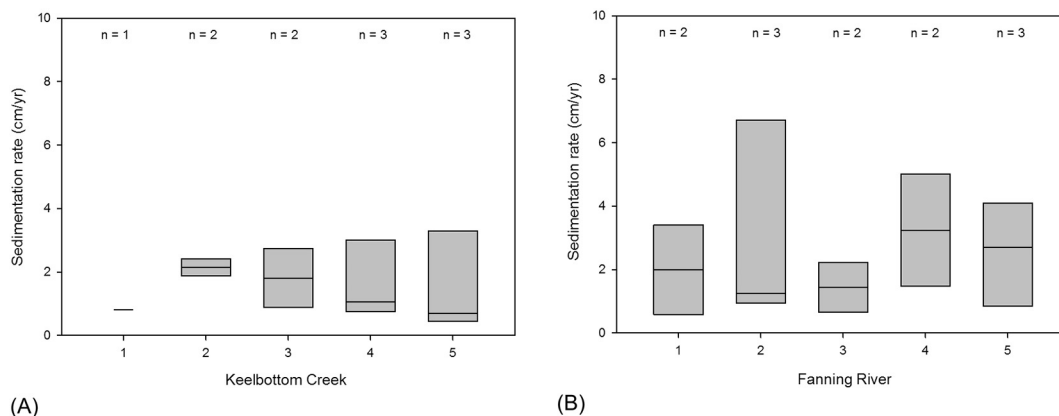(A)   (B)

Fig. 11. Sedimentation rates of the benches in each catchment grouped by sampling site/location (A) Keelbottom Creek (B) Fanning River. The centre line in the box-plots represents median values.
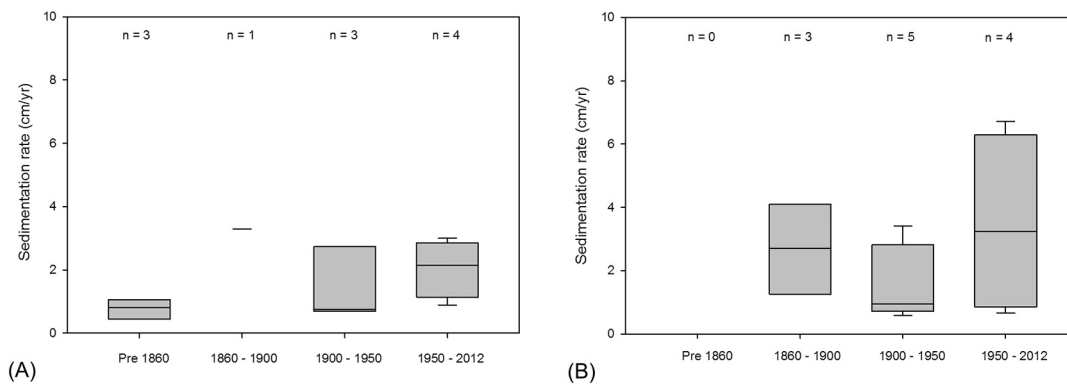
Fig. 12. Sedimentation rates of the benches in each catchment grouped according to deposition period for (A) Keelbottom Creek (B) Fanning River. The centre line in the box- plots represents median values.

have been a dominant, but only partial contributor to the end of catchment sediment flux.

5.4. Linking sedimentation rates to land use history

This study suggests that bench formation is likely to be a combination of all three processes proposed by Pietsch et al. (2015) and cannot be attributed to land use change alone (Fig. 13). Given that benches were present in Keelbottom Creek prior to 1850 and on Fanning River from 1850 to 1900, it is likely that these features were initiated by a change in climate and associated runoff in the region (Lough et al., 2015; Hughes and Croke, 2017). This change in runoff must have been coincident with a change in sediment supply, otherwise it would have resulted in bench destruction rather than creation (Pietsch et al., 2015). Some of the increased sediment supply may have come from intrinsic channel sources (e.g. channel bed and banks) (Kermode et al., 2015), but, it is also likely that some of this increase in sediment supply came directly from alluvial mine workings that were documented to have occurred along many creeks in the Upper Burdekin including Keelbottom Creek and Fanning Rivers (Roderick, 1981; Neal, 1984). It is acknowledged that grazing in the early settlement period (1850–1900) was focused in riparian zones as stock required access to water, so grazing by earlier settlers probably also contributed to increased sediment supply. However, the relatively low numbers and stocking densities of cattle in the region at that time are considered to have had a much lower impact than they do today. Large numbers of cattle, and moderate stocking densities (> 10 beasts per km^2), were not recorded in the Upper Burdekin until post 1950, which is generally much later than other parts of the Burdekin (Lewis et al., 2007).

Therefore, increases in the marine sedimentation rates (Lewis et al., 2014b), changes in the elemental concentrations in coral cores (McCulloch et al., 2003; Lewis et al., 2007) and changes in coral community structure including the collapse of some species (Roff et al., 2013; Clark et al., 2017) offshore from the mouth of the Burdekin River are also likely to reflect this land use and climate history. That is, land clearing and grazing did not occur instantaneously with the arrival of Europeans in the region in ~1862, and the initial increases in sediment flux recorded in coral cores by McCulloch et al. (2003) and estimated to occur in ~1870 are likely to be the result of climatically driven changes in runoff, and the local effects of mining. The low numbers of sheep and cattle in the catchment in the 1850–1870s, particularly in other areas of the Burdekin such as the Cape and Bowen area, are likely to have contributed to the increased erosion, but they were not the only or primary cause. This finding is supported by the presence of mercury, a bi-product of mining, in marine cores that dates to ~1910 (Lewis et al., 2014b) and also supported by the 10-fold increase in coral Mn in 1855–1856 (see Fig. 5c in Lewis et al., 2007), which is more closely aligned with the increase or change in flow regime. The 1855 time

period, loosely corresponds to the period when sheep were introduced to the region (data on exact numbers and locations are scarce), however, the numbers were extremely low, and most accounts suggest many of the sheep died due to adverse conditions.

In high energy, but ephemeral tropical systems, the delivery of material to marine systems is highly dependent on flow. In particular, the size of the event (m^3/s), the length of the event (hours to days) and the frequency (relative to drought). Erosion can occur during low flow or drought periods, but sediment will only be delivered to marine systems during large events. This was highlighted by data presented by McCulloch et al. (2003) that identified several drought breaking floods in the Burdekin in the 1700s. Thus an increase in rainfall and runoff (as recorded in the coral core flow anomalies of Lough et al., 2015) would likely have resulted in an increase in sediment delivery, even without a change in land use. The coincident introduction of mining and hard hooved animals have provided additional sediment for delivery, and thus exacerbated this process. Differentiating the influence of climate from land use on sediment flux will continue to be an important area of research (Wu et al., 2012; Wang et al., 2015).

Rustomji and Pietsch (2007) demonstrated that alluvial bench ages in the Murrumbidgee River in Southern Australia were dominated by OSL samples from 1869 to 1978 with little deposition after 1980. This decline was not considered to be related to changed rainfall or hydrology, and therefore the authors suggested that the catchment was undergoing a phase of landscape recovery. In this study, the numerous young (post 1990) OSL ages, and increasing sedimentation rates, suggest that the rivers are still actively accumulating sediment. Unlike the Rustomji and Pietsch (2007) study, the bench deposition rates in this study are not declining.

6. Conclusions

This study has provided important insights into the contribution of historical land use to the increase in fluvial sediment deposition. These findings have implications for studies that have investigated the delivery of sediment offshore of the Burdekin River basin using marine sediment cores (Lewis et al., 2014b) and coral geochemistry analysis (McCulloch et al., 2003). The Upper Burdekin, along with the Bowen-Bogie basins, are known to dominate sediment delivery from the Burdekin basin, even after the installation of the Burdekin Falls Dam in 1987 (Maher et al., 2009; Bainbridge et al., 2014; Croke et al., 2015). This study identified that the initial increase in sedimentation within Keelbottom Creek and the Fanning River was most likely associated with a climatically driven change in runoff, and the local effects of mining and grazing. Grazing has likely had a significant effect on bench sedimentation rates in this area, particularly in the initial settlement period (~1860) when stock congregated along streamlines, however, the peak influence of grazing did not take place until after the 1950s.
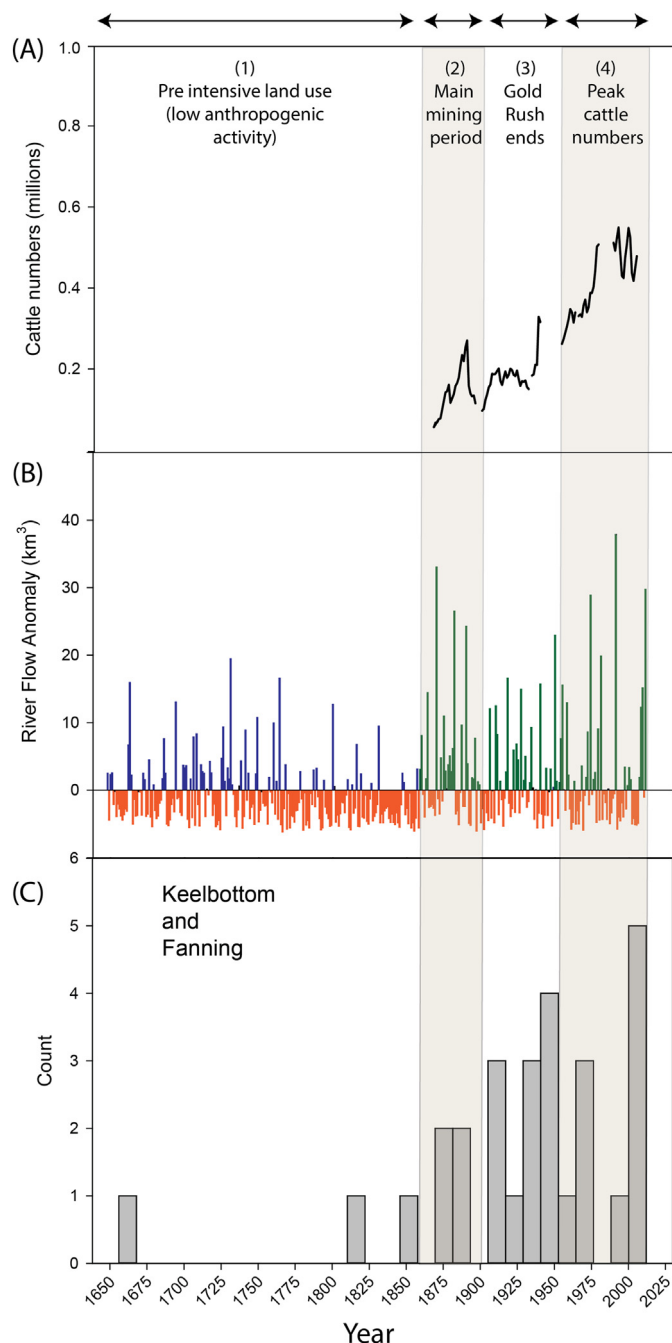
Fig. 13. Schematic diagram showing (A) the four general land use periods (1) pre-1860; (2) from ~1860 to 1900, (3) 1900 to 1950, and (4) 1950 to 2012. Cattle numbers for the Upper Burdekin are represented by the black line (Source: Lewis et al., 2014a). The beige bars are to delineate the time periods (B) the change in reconstructed Burdekin River flow (anomalies, deviation from the mean) from 1648 to 2011 based on coral core data (Source: Lough et al., 2015). The green lines show the period of increased flow frequency post 1860; and (C) OSL frequency histogram plots for Keelbottom Creek and Fanning River combined (Note Bin widths were 30).The histograms for the individual catchments are shown in Fig. 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mining within the channel network has largely ceased in the Upper Burdekin, and although it has likely had a considerable contribution to the legacy sediment generated in the Burdekin, grazing (and associated infrastructure such as roads) is the major land use actively driving erosion in this area today. Grazing is also likely to be exacerbating any damage done by mining and slowing its recovery.

It is likely that mining has caused a significant increase in the sediment loads in the Upper Burdekin, similar to other parts of Australia (Shakespear et al., 1887; Knighton, 1987; Bartley and Rutherfurd, 2005), as well as California (James, 1989), Papua New Guinea (Pickup et al., 1983) and the UK (Lewin and Macklin, 1986). However, further detailed investigations downstream of historical mining areas (e.g. Ravenswood mine fields) would provide greater insights into the specific timing and impact of mining in the Burdekin catchment and the GBR.

Understanding the rates and timing of bench development provides important insights into the timing of anthropogenic erosion in these catchments, but also into the likely buffers that will make measuring reductions in sediment yield due to land management improvement challenging (Fryirs, 2013). For example, a 10% reduction in fine sediment yield measured at the end of a catchment could be due to improvements in land management, or as shown in this study, may be related to increased fine sediment storage in bench deposits (cf. Trimble, 1983).

This study does not imply that there should be less investment in improved grazing land management in this catchment - quite the contrary. The study suggests that the impact of grazing on erosion and associated sediment deposition has been larger in recent decades, and it is likely to be exacerbated and potentially worsen in coming decades. Given the forecasted climate projections for this area (Power et al., 2017), there is an urgent need to make sure that all sources of sediment are minimised. The one saving grace may be that some of the increase in erosion will likely be off-set by an increase in sediment deposition on alluvial features such as benches. However, a large proportion of the fine sediments, which are the most detrimental to the GBR, are not likely to be stored in these deposits, at least not in the wetter, steeper, headwater tributaries. It is now considered that the combination of increased thermal stress to corals, in combination with increased sediment loads associated with large floods, are likely to pose the greatest threat to coral ecosystems on the GBR (Clark et al., 2014; Humanes et al., 2017). Therefore managing both current, and legacy, sediment sources, will be critical for improving water quality to the GBR.

Author contributions

Rebecca Bartley: Field design, sample collection, data analysis and primary author of manuscript.

Chris Thompson: Sample collection, statistical analysis of OSL data and writing

Jacky Croke: Field design and writing

Tim Pietsch: OSL lab analysis and methods

Brett Baker: Field survey sampling and sediment analysis

Kate Hughes: Stratigraphic diagrams

Anne Henderson: GIS support and map preparation

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comments greatly improved the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2018.04.070.

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